19 THE POTENTIAL OF AN INTERACTIVE HMD

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Touted as having wide-spread potential ever since their appearance in the 1960s, helmet-mounted displays (HMDs) can be found in hands-free viewing applications (Melzer, 2006) and in visually coupled systems (Kocian, 1987) for military (Rash, 2001; see also Chapter 1, *The Military Operational Environment* and Chapter 4, *Helmet-Mounted Displays* of this volume), simulation and training (Casey and Melzer, 1991; Melzer and Porter, 2008; Melzer and Simons, 2002), and virtual reality applications (Barfield and Furness, 1995; Kalawsky, 1993). In trying to explain why they have not been more pervasive, Keller and Colucci (1998) identified factors such as cost, lagging technology, and sub-optimal ergonomics. Hopper (2000) suggested that the "visceral dislike" of wearing a monitor on one's head has not yet been countered by an application that sufficiently excites potential users. This is somewhat understandable, because too often HMDs have been developed without a *user-centered design* focus. The result was that some early designs were uncomfortable and caused eye strain (Moffitt, 1997), with a tacit demand that the user had to *adapt to* the technology, essentially becoming a slave to the whims of the hardware designer. This is unfortunate, because fundamentally, the benefit of the HMD lies not in the hardware itself, but in the way it aids users in performing their duties that helps them overlook the added weight, cost and complexity. So while the hardware obviously must meet certain application and user-dependent performance requirements (e.g., field-of-view, luminance, contrast, focus, binocular alignment, fit, weight and balance), to make the technology truly work, we must do more. In this chapter we explore the HMD as part of an interactive system, a role consistent with natural exploratory behavior, as described by the "perceptual loop" in Chapter 2, *The Human-Machine Interface Challenge* (Figure 2-2). We envision the HMD as part of a system that *adapts to* the user – Bonner, Taylor, Fletcher, and Miller, (2000) use the term "Cognitive Cockpit" and Schnell (2008) uses the term "Smart Avionics" – that is, one that enhances situation awareness, encourages or enables correct decision-making and reduces workload.

First, we examine the benefits of the HMD over traditional cockpit displays as enabling the pilot to spend more time looking outside of the cockpit. We then focus on situation awareness (SA), cognitive workload, and the associated information acquisition, model-updating and decision-making loop to examine how overloading the pilot can cause this loop to breakdown. From there, we discuss attention, multiple perceptual and cognitive resources and the implications of cross-modal sensory integration, followed by a discussion of some developments in HMD symbology. Finally, we explore ways in which a feedback loop that includes psychophysiological monitoring (e.g., encephalograms, evoked potentials, and ocular-motor measures) can provide real-time integration into the HMD system, and promises to optimize the human-machine interface enhancing situation awareness without contributing to cognitive overload. Advances such as these will allow HMDs to be taken beyond a hands-free display or a visually coupled system to where it can be considered a *cognitive prosthesis*,[1] assisting pilots in the face of overwhelming workload or physical stress that could compromise their mission or their life (Melzer, 2008).

This chapter is intended to be somewhat speculative, to project applications and enablers of the technology that have yet to be fully realized. While other authors in this volume have dealt with some of the basic perceptual, user interface and hardware-related issues, it is our intention to invoke thought and discussion about the future of

[1] The term *Cognitive Prosthesis* is taken from the brain injury rehabilitation literature. It is a computer-based, assistive, compensatory technology designed for individuals who through either injury or illness have acquired a cognitive deficit, thereby allowing them to participate in and navigate through the everyday world (Cole and Matthews, 1999).

HMDs by framing this chapter within a neuroergonomics[2] context. Thus, a better understanding of the ways humans perceive and react to incoming sensory information will allow designers to "radically rethink the design of human-machine system interfaces to optimize the flow and exchange of data between humans and machines" (Berka et al., 2007). Making HMDs fully interactive in these ways will lead to the emergence of more wide-ranging applications.

Why an HMD?

What makes the HMD better than other cockpit displays such as head-down displays (HDD) or head-up displays (HUD)? For the answer, we need to examine the essence of natural human exploratory behavior. In his classic text, Gibson (1986) describes the human as a *perceptual system*: "… the eye is a part of a dual organ, one of a pair of mobile eyes, and they are set in a head that can turn, attached to a body that can move from place to place." The implication is that the capabilities of this perceptual system are fully exploited only if it is free to explore the environment, a concept consistent with Piaget's (1952) thesis that exploration of the environment is fundamental to cognitive development in infants. Although cockpit displays have advanced from HDDs (requiring the head and eyes to be within the cockpit) to HUDs (allowing the head and eyes to be out of the cockpit, but limited to a single line-of-sight), the information critical to achieving situation awareness is still only available in a small region of the pilot's forward field-of-regard.

If, however, we link an HMD to the aircraft with a head-orientation tracker, it becomes a Visually Coupled System (VCS - see Kocian, 1987) that allows the pilot to take advantage of a fuller array of information by overlaying imagery or symbology that is reactive to head motion and which may be aircraft- or geospatially-referenced.[3] Now the HMD (as part of the VCS) expands the pilot's useful field-of-regard by allowing him/her to turn head *and* eyes to better perceive the environment. This gives the pilot access to information when looking outside the limited field-of-view of the HUD with cues to guide or direct attention to specific objects, landmarks or targets because the pilot's threats are not just in front of the aircraft[4]. A head-tracked HMD also allows the pilot to direct another aircraft or crew member to an object or location, or to bring weapons to bear on a specific off-boresight target simply by looking at it (Arbak, 1989; Merryman, 1994), significantly enhancing the aircraft's effectiveness as a weapons or observation platform. Thus, the HMD aids the pilot by: 1) reducing time spent with head down in the cockpit, 2) reducing perceptual switching time from cockpit to outside world (i.e., attention, vergence and focus), 3) presenting imagery that can be either earth- or aircraft-referenced, and 4) allowing the pilot to be directed to a target of interest and then to track the target as it moves (Yeh, Wickens and Seagull,

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[2] "Neuroergonomics focuses on investigation of the neural bases of such perceptual and cognitive functions as seeing, hearing, attending, remembering, deciding and planning in relation to technologies and settings in the real world... Knowledge of how the brain processes visual, auditory and tactile information can provide important guidelines and constraints for theories of information presentation and task design…Neuroergonomics has two goals: 1) to use existing and emerging knowledge of human performance and brain function to design technologies and work environments for safer and more efficient operation; and 2) to advance understanding of brain function in relation to human performance in real-world tasks" (Parasuraman, 2003; 2007). Neuroergonomics requires an understanding of how the brain processes auditory, visual and tactile stimuli as a basis for designing interfaces between humans and technology. It is not intended to be just a laboratory science, but one that should form the basis for interaction with technologies in the real world (Hancock and Szalma, 2003)

[3] Imagery on the HMD can be displayed in three frames of reference: 1) aircraft-referenced (such as the shape of the front of the aircraft), 2) earth-referenced (either real objects such as runways or horizon lines or virtual objects such as safe pathway in the sky, threat/friendly locations engagement areas, waypoints, and adverse weather), and 3) screen-referenced (such as altitude, airspeed, or fuel status) (Yeh, Wickens, and Seagull, 1998; Procter, 1999).

[4] In simulation studies with an HMD, pilots spent 70 to 80% of their time *not* looking along the line of sight of the HUD (Arbak, 1989), which is especially critical during nap-of-the-earth (NOE) flight. Geiselman and Osgood (1994) found that when provided with useful ownship information, test subjects look further off-boresight for longer periods of time.

1998). Rogers, Asbury and Haworth (2001) surveyed a group of AH-64 Apache helicopter pilots to explore areas in which HMDs could enhance their abilities. Their list included: 1) aiding in maintaining situation awareness, 2) allowing for improved target acquisition, 3) aiding in moving through their environment, 4) improving symbology without increasing clutter, and 5) providing additional warning information. The results reinforce the intent of this chapter as these aviators had first-hand experience with the Integrated Helmet Display and Sighting System (IHADSS, Rash, 2001) and it reveals something about the support for HMDs by pilots with first-hand knowledge of their capabilities. In the next sections, we will examine ways to further enable these advantages.

Situation Awareness and Cognitive Workload

Achieving situation awareness (SA) for the pilot is the primary and ultimate goal of the HMD designer. A commonly accepted definition of SA divides it into three levels: *"*Level 1) *the perception of the elements in the environment within a volume of time and space,* Level 2) *the comprehension of their meaning, and* Level 3) *the projection of their status in the near future"* (Endsley, 1995a) (Figure 19-1). This definition has been applied to tasks as diverse as air traffic control, battlefield management, medical procedures, firefighting, weather forecasting, football and any environment where a timely and global understanding of a dynamic situation is vital (Endsley, 2000; Endsley and Hoffman, 2002; Uhlarik and Comerford, 2002). For the pilot, SA can be thought of as a dynamic interpretation of constantly changing information considering the future state of the aircraft and environment, essentially an understanding of the "*whatness*, *whereness* and *whenness*" (Helmetag et al., 1999) of the environment through which a pilot must fly and fight. To have full SA, the pilot gathers information (Level 1 SA) and creates a mental model of the current state of the aircraft and surrounding environment (Level 2 SA). The information actually used – sometimes inconsistent and disjointed – may include visual, auditory and/or tactile *meta-knowledge.*[5] With this information, pilots use their training and cognitive processing skills (including short-term, working and long-term memory resources) to convert the *navigational* knowledge – derived from an egocentric point of view, generally acquired by scanning the cockpit instruments and the outside world, listening to the multitude of communication channels and sensing the behavior of the aircraft – into *configurational* knowledge or a "bird's-eye" view of the current situation.[6] But since the environment (and aircraft status) is constantly changing, this mental model is both dynamic and accretionary, requiring the pilot to repeat the cycle of information gathering, information digesting, model building and prediction over and over again for the duration of the flight,[7] while using a minimum of workload[8] or effort. The optimal state is where the pilot has full SA but is only under a moderate or light workload.

But depending on the amount of data presented, the way in which it is presented, the state of the aircraft, and the sum of all other distractions, the process of *cognitively digesting* incoming data to produce and update an accurate SA model taxes the pilot and breaks down when his capacity to process the information *exceeds* his resources. In other words, "In the complex and dynamic aviation environment, information overload, task complexity, and multiple tasks can quickly exceed the aircrew's limited attention capacity. The resulting lack of SA can result in poor decisions, leading to human error" (Endsley, 1995b). SA fails most often when cognitive overload causes the pilot to lose touch with Level 1 SA (i.e., perceiving the environment). A recent assessment of

[5] The term "meta-knowledge" is used here to mean *knowledge about knowledge* from sensors and cockpit displays or data that may be one step removed from the actual information itself. The intent is to emphasize the additional cognitive processing needed by the pilot to convert it to useful knowledge.
[6] This mirrors a body of work in cognitive mapping, in which someone exploring a new environment is gradually able to create a schematic map of the area in his/her head after having explored it (egocentrically) on foot (Kuipers, 1978).
[7] Note here the similarities here to the perceptual loop described in Figure 2-2 of Chapter 2, *The Human-Machine Interface Challenge* and to John Boyd's OODA Loop (for Observe, Orient, Decide, Act) for fighter pilots (Boyd, 2007).
[8] Workload is a multidimensional construct (Hancock and Szalma, 2003), sometimes called the "flip side of the same coin" as SA (Endsley, 1993). It is commonly defined as the demand on attentional and cognitive resources required maintaining SA.

U.S. air accidents found that 80% occur at this level of perception, with the worst failures falling into the sub category (37%) of "failure to monitor" (Smith, 2006). This happens when aircrews are distracted because of

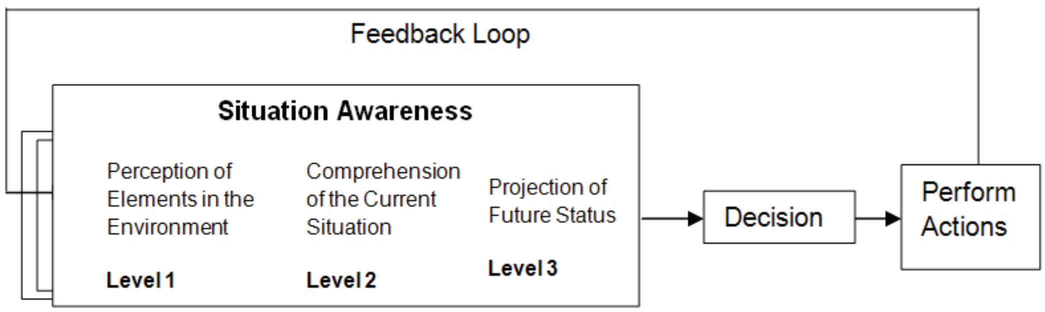

Figure 19-1. Shows a nested Level 1, Level 2 and Level 3 model of Situation Awareness and the continuous feedback loop necessary to maintain SA (after Endsley 1995a).

cognitive overload that they fail to address the real issues at hand. Factors such as divided attention, having too much incoming data, or having to expend too much cognitive effort limits the pilot's ability to monitor the current status and to predict the future state of his aircraft. Thus: "how quickly one converts navigational (egocentric) knowledge to survey ("God's-eye") knowledge and is able to achieve true situational awareness depends partially on *the manner in which the information is presented, the cognitive capabilities of the individual and the amount of cognitive energy the individual is willing to expend in the effort*." (Helmetag et al., 1999, emphasis added). Somehow, we must provide the pilot with information that is easily digested (or perhaps "pre-digested"), to reduce cognitive overload. Endsley and Hoffman (2002) refer to this as the Lewis and Clark Principal: "The human user of the guidance needs to be shown the guidance in a way that is organized in terms of their major goals. Information needed for each particular goal should be shown in a meaningful form, and should allow the human to directly comprehend the major decisions associated with each goal."

Attention, Cognitive Resources and Cross-Modal Integration

The modern pilot is faced with a complex array of tasks (i.e., aviate, navigate, communicate, and systems management – see Wickens, 2007) that by nature require multiple cognitive and perceptual resources, multiple attentional resources and multiple auditory and physical responses. The problem is how to direct the pilot's attention, enable the perception or acquisition of critical information (Level 1 SA), encourage the synthesis of the information (Level 2 SA) and provide a mechanism for the pilot to take action based upon the prediction of future state (Level 3 SA), within the pressures of flying, and the added limitation that the pilot's visual and auditory channels become progressively saturated. The goal is to find methods of presenting information, or ways to capture and guide attention that will not overwhelm the pilot.

Wickens and McCarley (2008) discuss five discrete types of attention[9] though they also provide a simpler definition which divides attention into just two categories: *filter* and *fuel*. Humans are faced with a constant barrage of stimuli which, if not *filtered* by attentional resources, would rapidly be overwhelming. If, however, when attending to a specific stimulus, available perceptual and cognitive resources can be energized to address the implications of this stimulus. This is the *fuel* aspect of attention. Improperly directed attention can reduce situation awareness (i.e., see Smith, 2006 and the implications for Level 1 SA for "failure to monitor") or increase workload by having the pilot attend to too many stimuli varying widely in priority. This filtering is the function of executive control, that part of the brain which allows attention to be directed to the stimulus of choice. When

[9] These are: focused, selective, switched, divided and sustained (Wickens and McCarley, 2008).

attention (or task or perceptual modality – Koch, 2001; Spence and Driver, 1997) is switched, there is an associated time penalty because of the serial steps involved in doing so (*goal shifting* followed by *rule activation* – Rubinstein, Meyer and Evans, 2001). With multiple attention shifts, we pay a larger penalty, and it raises the possibility that the goals will not be remembered upon returning to the original task. This can be overcome using mental models, frequently observed in the different ways experts and novices perform in high workload situations with high information load. Experts use shortcuts such as prioritization, and "gistification" to achieve Level 1 and Level 2 SA (Endsley, 2000). Experts may also pattern match, then load response scripts to prototypical situations or schema. Doing so may allow the pilot to achieve Level 3 SA without having to overload working memory. But in drawing upon schema, the pilot may be subject to situational biasing, possibly reducing his responsiveness to novel situations or stimuli.[10] Thus the pilot also needs to recognize when the information is in conflict with previously learned models and to modify the response,[11] though there is an associated increase in workload and communications (Marshall, 2007b). Problems arise when the executive control function is continuously over-tasked, and the pilot does not have enough reserve capacity to plan out behaviors required to accomplish the complex task of flying. *Unlike* someone who has suffered brain damage, this is a temporary affliction. However, *like* someone who has suffered brain damage, they lack the resources to make complex decisions associated with the aviate, navigate, communicate and systems management tasks. This is where the cognitive prosthesis approach can help (Cole and Matthews, 1999 and Melzer, 2008), by lightening their cognitive load and properly guiding them through difficult situations.

Models in the literature provide a better understanding of the issues surrounding the ways humans perceive and react to incoming information and how to enable the human-machine interface without causing cognitive overload. In his Multiple Resources Theory (MRT), Wickens (1980; 1984; 2002a) provides a framework for predicting performance effects when the pilot is required to execute multiple simultaneous tasks and distinguishes between and within three stages of cognitive processing. He posits that there will be greater interference (and subsequent increased workload) between two tasks if they share the same pool of resources which draw upon physically separate cortical functions:

- *Input perceptual or sensory modalities* (auditory vs. visual) – It is easier to divide attention between hearing and seeing (i.e., auditory/visual) tasks than between two auditory (auditory/auditory) or two visual (visual/visual) tasks, because the sensory modalities require separate resources (drawing upon the separate auditory and visual sensory cortices).
- *Central processing stages* (perceptual and central processing/cognitive vs. response) – Working memory resources used for perceptual and cognitive activities are the same; and they are separate from those that help in executing responses (drawing upon the right and left hemispheres).
- *Response codes* (spatial versus verbal) – Verbal and spatial processes or codes used in perception, working memory, or responses depend on separate resources, which can account for individuals' ability to simultaneously perform well manually and verbally (because they draw upon the different hand and mouth/respiratory regions of the motor and pre-motor cortex).
- *Channels of visual information* (focal versus ambient) – There are two channels of vision, the focal and the ambient that utilize separate resources (nominally in the central and peripheral areas of our vision, respectively).

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[10] It is also important to consider the (possibly undesirable) implicit feedback and filtering loops between each nested element within SA. These may manifest themselves when expectations bias perceptions, with at times disastrous consequences (see previous chapters) because it may cause the pilot to reject valid inputs and "loose touch" with Level 1 SA.

[11] Here the SA loop starts to overlap with sensemaking. While the former is generally associated with fitting of data into an already-established model, sensemaking is the attempt to find understanding of disparate and disjointed information by creating a new model (Weick, Sutcliff & Obstfeld, 2005; Leedom, 2001).

MRT says that resources needed for perception and cognition are the same, both of which involve working memory. Thus the resources required to gather knowledge which forms the basis of Level 1 SA are those same resources needed to create and manipulate the model in working memory, which is key to Level 2 SA, the understanding of the current situation. In addition, any complex mental manipulations of the data needed to arrive at that determination will be the same resources needed to determine the future state of the aircraft.

Wickens (2002a) also separates the visual channels into focal and ambient modes. The *focal* mode generally lies in the central region of vision and is dedicated to answering the "What?" about our environment. It typically requires our attention, is sensitive to light level (and our inherent refractive error) and a full range of spatial frequencies (Leibowitz, Shupert and Post, 1985). Under stress from shifts in attention, the individual may suffer a visual narrowing in the focal visual mode due to shifts in attention, which may also contribute to change blindness (Wickens, 2002b).

The *ambient* mode of vision, on the other hand, addresses the question of "Where?" Though overlapping somewhat with the focal mode, it is generally found in the periphery of our vision, and acts together with our vestibular system to help with spatial orientation. It requires only low spatial frequency information, and is more susceptible temporal frequency such as movement and flicker, though less sensitive to refractive error and ambient light level. The importance for HMDs is that the ambient visual mode is thought to be "pre-attentive" or automated and therefore may require *no cognitive resources at all* (Uhlarik and Comerford, 2002). Thus the ambient mode of vision will likely not suffer from attentional narrowing due to overload and may be an important path to improving SA without increased workload.

Wickens (1980; 1984) states that separating the sensory modalities – auditory versus visual versus tactile – allows attention to be divided. Spence and Driver (1997), however, take issue with Wickens' interpretation of absolute separation of resources and posit that there are limitations on their independence due to cross-modal linkages between these covert (i.e., internal processing) visual, auditory and tactile attentional resources. For example, if the separate tasks (which use separate resources) place high demand on the individual – as in the case of time-sensitive responses – subjects will tend to serialize their responses rather than operate in a truly parallel manner. The distinction may be a bit more subtle, though, in that Wickens' resource separation focuses on the perception, cognition and response to *continuous* tasks versus Spence and Driver's focus on discrete tasks requiring attentional shifts. These latter researchers point out that if an event is expected in one sensory modality, and it occurs in another, there is an attentional penalty due to the modality shift. They demonstrated that if a subject was expecting a cue in an auditory or visual modality, but it occurred as a tactile cue, there was a 16% performance lag. Furthermore, they found that "pre-cueing" in one mode can enhance the attentional resources and perception of an event in another mode. This is especially true for auditory and visual events that occur from the same spatial location, though there is still an attentional advantage even if they don't. Thus, the three different sensory modalities can act effectively as pre-cueing "notifiers" of an event in another modality in various combinations. The most effective appears to be an auditory cue, especially when used to notify the subject of a time-critical event, provided it is presented within 300 milliseconds (ms) of a visual event (Pouget, Deneve and Duhamel, 2004). Hameed et al., (2007) found that a directional tactile cue improved visual detection rates by 43%. This process which combines visual, auditory and tactile sensory signals relating to the same object in time and space appears to be something humans excel at, taking advantage of multi- and intermodal redundancies.[12] When integrating audio earcon and visual icon cues[13] into a display, it is important that we understand these

[12] The only notable exception is that a visual notifier *does not* effectively cue an auditory event (Spence and Driver, 1997).

[13] *Earcons* are abstract sounds where the meaning must be learned and where the meaning forms a hierarchical structure. The typical example is groups of musical notes to designate types of input errors. *Auditory icons* are natural sounds that have a meaning associated with the object they represent. Throwing a document in the desktop trashcan can be accompanied by a crumpled-paper sound to symbolize deleting a file within the context of the desktop metaphor (Houtsma, 2003). Care must be taken, however, to ensure that the meaning is clear, that the messages are synchronized and that there a valid perceptual *co-occurrence* between them (Bertelson and de Gelder, 2004)

issues of multisensory integration so the pilot can make accurate and meaningful statistical inferences (Pouget, Deneve, Duhamel, 2004) about the intent of the multimodal stimulus.

Research has shown that spatial or three-dimensional (3-D) audio[14] can dramatically improve safety and performance, decreasing workload and improving SA by superimposing geospatial directionality on radio communications and by using the audio cues redundantly with visual cueing to direct the pilot's attention for alerts and warnings (see Bolia, 2004, for an excellent collection of papers on the subject). The benefit is to increase situation awareness and decrease workload by decreasing audio clutter, by providing an intuitive spatial location for warnings and alerts, and by redundantly coding external threats and waypoints as an audio cue to direct visual attention. 3-D audio cueing especially when used with an HMD, reduces search time and improves situation awareness for the user (Bolia, D'Angelo, and McKinley, 1999; Flanagan et al., 1998; Houtsma, 2003; see also Chapter 14 of this volume, *Auditory-Visual Interactions*).

We perceive the direction of sounds ("the eyes follow the ears" – Wenzel, 1992) by processing temporal, intensity, phase and spectral differences between the sounds reaching our left and right ears. These differences result from the interference of the head, pinnae, and torso with a sound wave, a transform called the Head Related Transfer Function, or HRTF.[15] Accuracy is less with auditory tracking than with visual tracking so relying on the former for accurate cueing is not appropriate since this is not how – ecologically speaking – we search and navigate through and within the real world.

Spatial hearing also allows the advantage of discriminating sounds in the presence of noise. Providing a spatial separation between the audio source of interest and interfering noise improves the listener's ability to detect and understand the audio content, much like the so-called *Cocktail Party effect*, where we can listen to different conversations within a crowded room simply by attending to them (Cherry, 1953). Similarly, spatial hearing improves the understanding of speech when there are competing sources such as multiple talkers. Assigning a distinct spatial direction (and location) for each source dramatically improves intelligibility compared to when they originate from the same location. Such an advantage would seem natural in an aviation cockpit; though it appears there is much improvement needed with spatialization protocols.[16]

Examples of HMD Imagery

Information displayed to the pilot must be only that which is essential for the task at hand and must be presented so that interpreting the data does not overload the pilot's already-taxed perceptual and cognitive resources. In this section, we present examples of HMD symbology that have been shown to improve performance, i.e. imagery that: 1) provides cognitively pre-digested information, 2) provides stable frames of reference and 3) stimulates the

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[14] 3-D audio refers to radio channels, cockpit warnings, threat and target designations that have a spatial direction and range (also discussed elsewhere in this book – see Chapter 5, *Auditory Helmet-Mounted Displays*).

[15] The Head-Related Transfer Function (HRTF) refers to binaural hearing effects resulting from the location of our ears on either side of our head. The HRTF consists of three components: Interaural Time Delay (ITD - sounds reach the closest ear first, followed after a short time delay by the sound reaching the other ear), Interaural Intensity Difference (IID - the closest ear hears the full intensity of the sound, the farthest ear, shadowed by the head, hears a reduced intensity of the sound), and finally, spectral filtering from the pinnae (the outer ear filters certain frequencies depending on their fore/aft or up/down location). Because the HRTF differs from person-to-person, it is difficult to generate a *generic* HRTF that will accurately restore "hear-through" for all users (Chapin et al., 2004) though there are ongoing efforts in this area to overcome these limitations (McIntire et al., 2008).

[16] There is no standard or protocol for assigning radio channels or avionics warnings to either relative or absolute geo-spatial locations. For example, should the wingman or the control tower audio come from the correct geospatial location relative to ownship or from some standardized location? In addition, there is no standardized set of non-speech audio warnings and alerts, such as low oil, threats, low fuel, weapon status, and most aviation helmet systems are do not support 3-D audio because they are monaural.

ambient mode of vision. In all cases, we will assume that the HMD is part of visually coupled system (Kocian, 1987; Rash, 2001) in which a tracker communicates helmet-referenced orientation data to a sensor, a computer or a mission processor.

Early HMDs used a simple reticle similar to the one shown on the left in Figure 19-2. The targeting cross in the center is boresighted to the aircraft's weapons and the small diamonds around the edges indicate a "look-to" direction for the pilot. This simple symbology unlocks the pilot from the forward line-of-sight of the aircraft HUD, giving him the ability to designate targets and to aim and deliver weapons off-boresight, and has been shown to have profound implications as a force multiplier (Arbak, 1989; Merryman, 1994).

Compare this with a more sophisticated symbology set on the right side of Figure 19-2 that could be found on a more recent fixed-wing pilot's HMD. The circle within a box at the end of the "look-to" arrow is the target designator box (or "TD box") which combines the center cross and directionality diamonds of the early version. The later version also provides more flight data such as altitude, airspeed, heading, attitude, and weapon status. Having this information readily available anywhere the pilot is looking frees him from

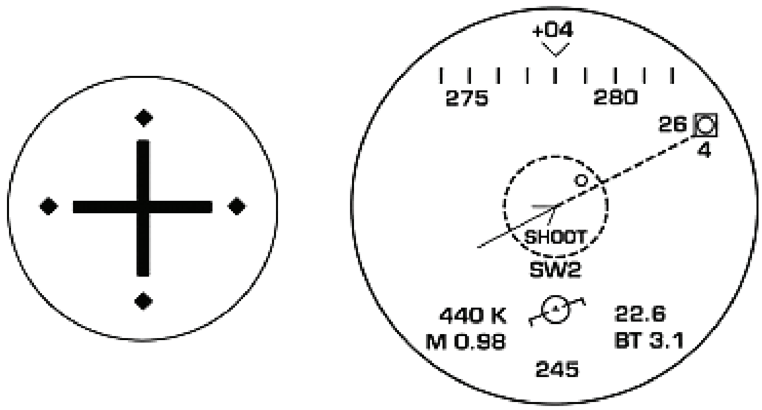

Figure 19-2. Comparison of an early HMD reticle (left) with a more sophisticated symbol set intended for use on fixed-wing fighter HMDs (after Melzer, 2006).

having to look inside the cockpit or forward at the HUD to gather that same Level 1 SA information. But with the exception of the improved targeting reticle, it is only a re-mapping of the information that might normally be found on the HUD and results in a cluttered out-the-window view. With the introduction of HMD-based off-boresight tracking and targeting, the U.S. Air Force has been examining ways to ease the pilot's transition from on-boresight HUD symbology, because pilots complain that there is too much symbology on their HMD. One solution is to simply de-clutter the imagery when the pilot looks off-boresight, with the standard symbology returning when the pilot looks back "on boresight" (Albery, 2007), or to permit the pilot to customize the declutter mode depending on preference and situation.[17] In a series of papers, Jenkins and his colleagues (Jenkins, 2003; Jenkins, Turling and Brown, 2003; Jenkins, Sheesley and Bivetto, 2004 and see also Albery, 2006) evaluated the Advanced Non-Distributed Flight Reference (Advanced NDFR) for displaying ownship status information that is easily read without cluttering up the HMD field-of-view, but which provides sufficient information to allow the pilot to feel confident enough to spend more time off-boresight. The key is an open circle – the arc segment attitude reference (ASAR) originally conceived by Dornier in 1987 – which changes as a function of aircraft attitude as shown in Figure 19-3. At straight and level, the only part showing is the bottom 180°. As the pilot climbs, the circle gradually closes until it becomes a full circle at a 90°-climb. Likewise, as the pilot dives, the circle gradually shrinks until it is only a small segment at a 90°-dive. Jenkins and his colleagues

[17] The only caveat is that critical data must be "re-cluttered" at some point so the pilot does not miss a key piece of information.

improved the original NDFR by adding digital flight path angles, altitude, airspeed and heading to display of rate-of-change data. Simulation studies and flight test results indicate that this was well accepted by pilots and allowed them to spend more time looking off-boresight, out of the aircraft.

In a 1998 study, several alternate HMD imagery concepts were investigated for fixed-wing pilots at the U.S. Naval Weapons Center and Boeing's Phantom Works (Proctor, 1999), including geostationary "X-ray vision" imagery that allowed pilots to see through hills and ridges when flying terrain-masking routes, "message bubbles," virtual sign posts and geospatially-fixed synthetic grids placed over *actual terrain contours*. Message bubbles and other message icons were placed in the display where no other key information was located, freeing the pilot from having to mentally "declutter" the imagery. It allowed the pilots to go quickly from *egocentric* knowledge to *survey* knowledge with a minimum of cognitive processing, and is consistent with our previous contention that pre-digesting the information eases the transition from Level 1 to Level 2 SA.

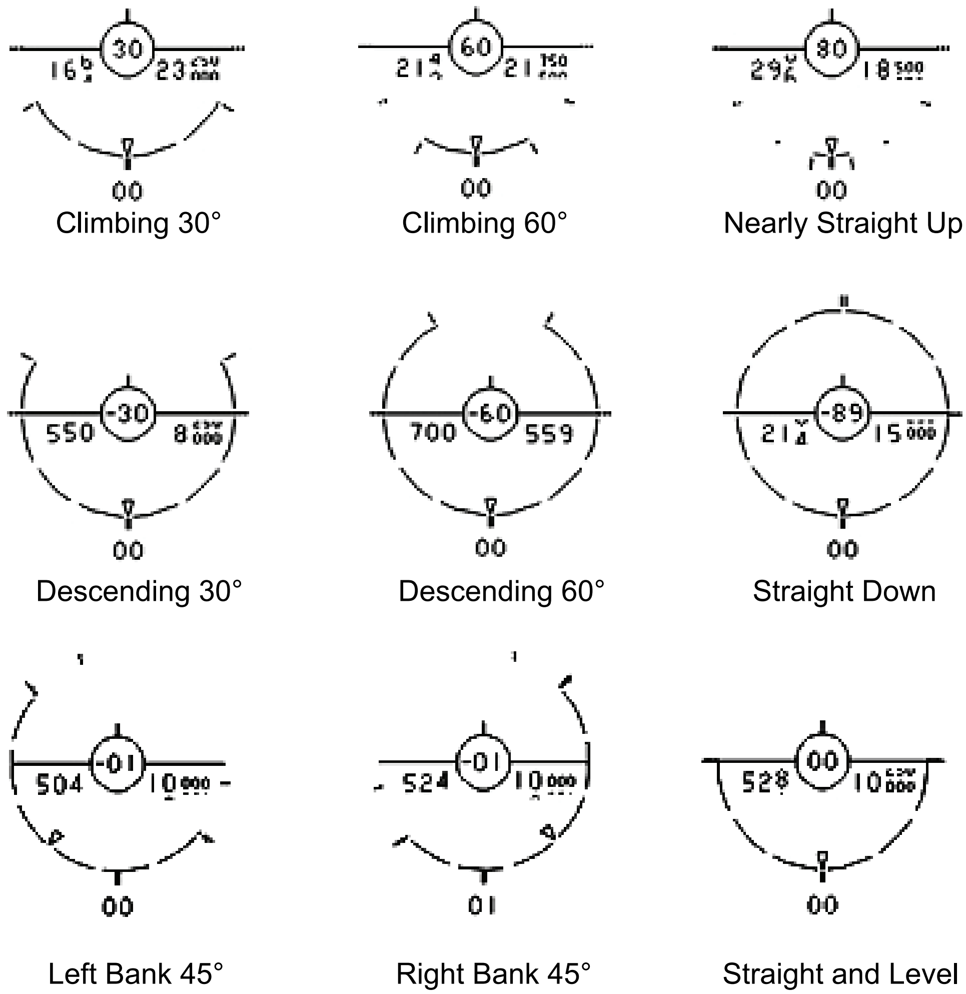

Figure 19-3. Advanced Non-Distributed Flight Reference symbology for fixed-wing HMDs shown in various phases of flight orientation. The number in the central circle indicates is the digital flight path angle. The numbers to the left and right are the airspeed and altitude, respectively. The number at the bottom shows the heading. (Used with permission, U.S. Air Force, 711th HPW/RHCV.)

Many domestic helicopters – with the notable exception of the AH-64 Apache – are equipped for night flight with an HMD in the form of the cathode-ray tube (CRT)-based NVG-HUD mounted on the Aviator's Night Vision Imaging System (ANVIS) goggles. The symbology is not head-tracked and thus neither geo- nor aircraft-stabilized (Yona, Weiser and Hamburger, 2004). Rather, it is generally a re-mapping of the head-down display information that would otherwise be readily accessible to the pilot during daytime flight. As part of the Air Warrior Block 3 program, the U.S. Army specified that the next generation of HMDs provide "*intuitive situational and system awareness displays* that permit pilots to fly the aircraft continuously with heads-up, eyes out regardless of environmental conditions" (U.S. Army, 2003, emphasis added). While helpful, it is generally felt by many pilots that this version of the NVG-HUD does not meet the definition of "intuitive situational awareness displays."

Still and Temme (2001) developed a symbology set called "OZ" to provide a graphical depiction of aircraft position and orientation (Figure 19-4). Their concept uses a star-field metaphor to map the external world into a coordinate system that displays both translations and rotations, shows the aircraft's attitude and location within the external world and takes advantage of the natural human perception of flow fields (Gibson, 1986). OZ enables traditional instrument panel information to be obtained at-a-glance instead of requiring the pilot to sequentially scan and interpret the individual dials and gauges.[18] In a more recent study, Still and Temme (2008) expanded the OZ symbology as an aid to helicopter pilot trainees learning the difficult task of hovering. Their results showed a reduction in training time to reach proficiency because the OZ symbology helped the students learn to interpret the complex motion cues in a helicopter. Though specifically designed for use with a HDD, there is fundamentally no reason why this same symbology could not be used with an HMD.

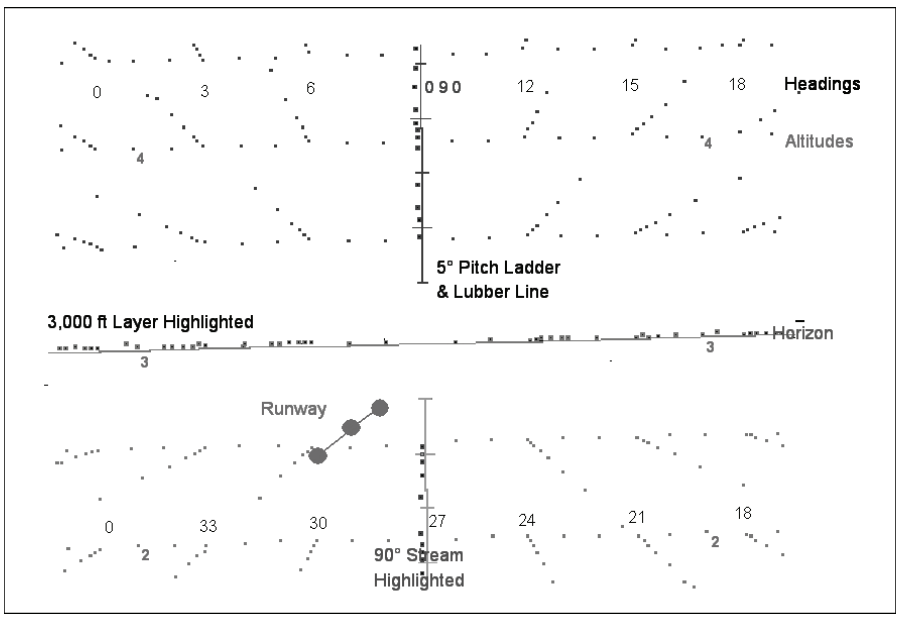

Figure 19-4. OZ symbology set which uses a star field metaphor to show flowfield, elevation and attitude. (Imagery courtesy of Dr. David Still and Dr. Leonard Temme, U.S. Army Aeromedical Research Laboratory, Ft. Rucker, AL, used with permission.)

Rogers and Asbury (2007) created a clock obstacle warning icon as part of their Rotorcraft Obstacle Avoidance Display (ROAD) (Figure 19-5) that could be unobtrusively located on the pilot's HMD to indicate the relative

[18] Hansen, Rybacki and Smith (2006) use the term: "synthesize the dials" to describe this part of the process.

location of a possible collision threat. This simple icon was very well received by the test (pilot) subjects who were impressed with how intuitive it was. Note the "splat" marker at the upper right hand side that indicates the direction of a potential collision.

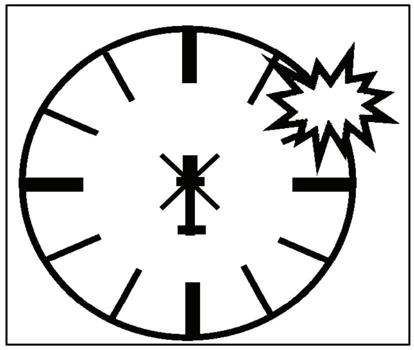

Figure 19-5. A Clock Obstacle Warning used in the Rotorcraft Obstacle Avoidance Display. Note the orientation of the helicopter and the potential collision direction. (Rogers and Asbury, 2007, used with permission).

A special imagery set designed by *Primordial* (Milbert, 2005) for ground soldier applications takes advantage of both conformal symbology and lessons-learned from the video game industry by indicating key points of interest or navigational information and their location relative to the soldier's "forward" position. A small, semi-transparent display window in the lower corner rotates as the soldier turns his head and body, providing a survey map view of the surrounding environment with forward indicated as the "up" direction (Figure 19-6), giving the soldier a better understanding of the surrounding environment.

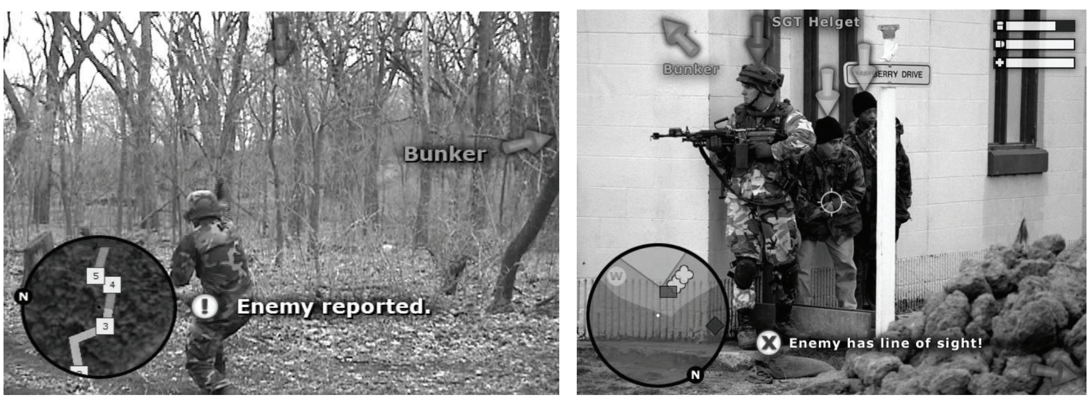

Figure 19-6. Conformal symbology for the ground soldier with a survey map view in the lower left that provides orientation of threats or waypoints in space (from Milbert, 2005, used with permission).

One finding throughout the literature is the benefit of locating conformal imagery or intuitive icons (e.g., virtual sign posts, synthetic grids, threats, safe path in the sky, horizon, ground, other aircraft, or landing field) in a geo-stabilized mode placed where they actually are in space. Wickens (2007) contends that conformal HUD imagery is more readily understood because the earth-referenced information is easily fused by the pilot - simplifying the Level 1 and Level 2 SA steps – because the outside world object moves with the imagery and the pilot intuitively links the two together (Yeh, Wickens, and Seagull, 1998). Doing so intuitively transforms the cockpit-derived *meta-knowledge* to earth-referenced data so the pilot is not required to derive their real location in space. A simulation study by Rogers, Asbury and Haworth (1999) demonstrated the efficacy of this concept by presenting earth-referenced symbology for waypoints and engagement areas (EA) on a head-tracked HMD with dramatic improvements in pilot performance. Using experienced AH-64 Apache aviators, their study demonstrated an impressive 300% improvement (287 feet vs. 878 feet) in waypoint accuracy and 430% improvement (262 feet vs. 1,130 feet) in landing point accuracy, a 12,000% improvement (14 feet vs. 1,666 feet) in engagement area fire sector identification accuracy with a *55 to 69%* reduction in overall workload (when using the waypoint symbols and EA symbols, respectively).

In work intended for general aviation application, Theunissen et al., (2005) created a predictive pathway in the sky to show the pilot the future position of the aircraft, making this part of his Level 3 SA process easier. Rogers, Asbury, and Szoboszlay, (2003) took this a step further and created a Flight Path Marker to overcome some of the problems with previous "pathway in the sky" efforts which only showed a projected tangent to the current (usually) curving flight path, not the actual predicted flight path itself. In experiments with experienced helicopter pilots, Rogers and his colleagues validated their approach with statistically significant improvements in: 1) minimizing the number of ground strikes, 2) mean roll direction changes, and 3) mean overall workload rating, clearly showing how pre-processing the flight path data allows more of the pilot's energies to be spent flying the aircraft than thinking about the future position.

In this same study, Rogers, Asbury, and Szoboszlay, (2003) displayed a set of concentric rings that were always oriented parallel to the horizon, located at a virtual separation of 50 feet in elevation and displayed out to the edges of the 60° HMD field-of-view. The rings provided the pilot a simple method of determining his aircraft altitude and attitude relative to level ground, avoiding the traditional ground versus figure confusion ("Am *I* tilted or is the ground?"). Their findings were significant in terms of: 1) touchdown groundspeed, 2) touchdown pitch error, and 3) overall workload rating. Because the rings were displayed as a wide field-of-view image, it also helped stimulate the ambient visual mode, the peripheral process which does not require conscious attention of the pilot, by pre-processing key pieces of flight imagery such as orientation relative to the horizon. Their results conclusively demonstrated that the pilots maintain their situation awareness with a reduction in workload.

A compounding factor derives from the pilot's seating position in the aircraft that may be a few meters removed from the actual location of a nose-mounted sensor, a situation that is exacerbated in low level flight or when the pilot turns his head 90° to the left or right (Antonio, 2008). One concept investigated on the – since cancelled – RAH-66A Comanche helicopter program was to display a stabilized wireframe outline of the forward aircraft structure. This was felt to be especially beneficial when the pilot was relying on the HMD for all imagery such as flying at night by giving the pilot a sense of orientation relative to the front of the aircraft.

Albery (2007) reported on a multi-sensory cueing system for fixed-wing aircraft called the Spatial Orientation Retention Device (SORD) where the pilot is provided visual, tactile and auditory cues. On- and off-boresight HMD symbology using the Non-Distributed Flight Reference (see also Jenkins, 2003; Jenkins, Turling and Brown, 2003) gives the pilot innovative and intuitive visual references to determine flight attitude using a relatively narrow field-of-view display. Tactile cueing augments the visual cues via torso-mounted tactors so as to convey aircraft attitude.[19] Out of normal attitudes are communicated by localized cueing on the pilot's chest. Further cues are provided with a 3-D audio system which indicates right or left banking. Combined with the Disorientation Analysis and Prediction System and EEG data, the SORD takes advantage of the multiple human sensor modalities to enhance situation awareness for the pilot, while reducing workload. As of this writing, the SORD has been transitioned to a Rotary-Wing Brownout program.

[19] See Albery (2006) and McGrath, et al, (2004) for a description of the Tactical Situation Awareness System (TSAS).

Measuring Workload and Situation Awareness in Real Time

The fast pace of modern aviation requires the pilot to remain engaged in key tasks that contribute to achieving all three levels of SA. Traditional methods of measuring SA and workload such as efficiency ratings, external observations of experts or self-evaluation can be tainted by bias and are certainly not conducted in real-time. Delayed or after-action indication of cognitive overload may be inadequate to capture time-sensitive loss of SA and to act upon it proactively to ensure mission success or to save lives. Researchers have investigated the use of neural and psychophysiological measures such as eye behavior (pupil diameter, blink and gaze), electroencephalography (EEG), heart rate, galvanic skin response (GSR), and functional near infrared imaging (fNIR) to identify cognitive states of workload, task engagement and fatigue (Craven et al., 2006; Schnell, Keller and Macuda, 2007; Wickens and McCarley 2008). Correlating these measures with their respective cognitive states could provide important benefits in training and flight. In the 1990s, the U.S. Air Force attempted to use EEG signals as a means to control complex aviation systems (Tepe-Nasman, Calhoun and McMillan, 1997[20]). As tantalizing as it appeared, it was felt by some to be ambitious for the time. A more direct approach may be to use these complex signals as operator status indicators and as inputs to a closed loop assessment-mitigation process.[21] This could provide an indication of problems such as cognitive overload (or *underload*[22]), fatigue, disorientation or a missed attentional cue and precisely when this occurred. The goal is to ensure that auditory, visual or tactile cueing will grab or channel the pilot's attention so that we avoid "inattention blindness" or the effect of "looked-but-failed-to-see." It may be possible to detect this change blindness using real-time measures of psychophysiological responses, because it is this lack of noticing – or change blindness *blindness* (Yeh, Wickens, and Seagull, 1998) – that is one of the first steps in the breakdown of the SA cycle.

Eye metrics such as pupil size, eye movements and blinks have been used to identify cognitive states such as engagement in problem solving, driving, and alertness/fatigue (Marshall, 2007a; Tsai et al., 2007). Beatty (1982) reviewed the task-evoked pupillary dilation data, finding a strong correlation of workload or cognitive processing load and the increase in pupil diameter that occurs within 100 and 200 ms of the task onset. He showed that the magnitude of pupil dilation is directly correlated with the magnitude of the effort required to address the task with the slope of the diameter increase directly correlated with task difficulty. He also found pupil dilations for near threshold detection of auditory and visual cueing signals as well as peak amplitudes of pupil dilation with memory tasks (increasing up to an asymptote of 7 digits), language related tasks (grammatical reasoning was found to be most difficult), arithmetic reasoning (difficult multiplications were found to be most demanding and resulted in the largest pupil increase) and difficult sensory discrimination tasks.

Marshall (2007a; 2007b) has developed the Index of Cognitive Activity (ICA) to effectively determine levels of cognitive workload from high-frequency increases in pupil dilation. The attractive aspect is its insensitivity to increases in light level that might be found in an aviation environment and would thus make the ICA compatible with an operational HMD. Marshall (2007a) also combined the ICA with other eye metrics such as pupil information, eye movements and blink status to determine cognitive states during problem solving (relaxed versus engaged), driving (focused versus distracted attention) and visual search (alert versus fatigued). She found that combining these measures made for a more robust assessment across individuals in the study rather than relying on any one metric individually.

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[20] This was, perhaps, a tribute to the 1982 film, *Firefox*, in which the aircraft is controlled by the pilot's EEG-interpreted thoughts.

[21] This is the focus of DARPA's Augmented Cognition (AugCog) program. "The new field of augmented cognition takes psychophysiological measurement to the next level by integrating continuous monitoring into closed-loop systems. By using the operator states as inputs, adaptively automated systems respond to user overload or under load, and react appropriately" (Berka et al., 2007).

[22] Cognitive underload refers to the state where the pilot is not fully engaged in critical tasks, possibly resulting in complacency and a failure to notice important events.

Synchronizing observed behavior with EEG data such as the time-based increase or decrease of the different brain wave rhythms[23] or various ratios of their values have allowed researchers to identify cognitive states including workload, distraction, drowsiness and training levels. Wickens and McCarley (2008) found a correlation of workload with increases in Theta band and decreases in Alpha band. Using a dense EEG sensor array (128 electrodes), Schnell, Keller and Mancuda (2007) found that the ratio of Beta/Alpha is indicative of cognitive workload and that Theta waves measured in the midline correlate with monitoring and memory tasks. Berka and her colleagues (Berka et al., 2004; 2006; 2007) have reported success in assessing cognitive states using a sparser EEG array (three to twelve sensors). Real-time EEG markers have also been found which directly correlate with levels of visual workload and situation awareness (Berka et al, 2007). Still other research has found specific EEG markers of spatial disorientation (Albery, 2007; Viirre, et al., 2006).

The N1 and P3 Event Related Potentials (ERP)[24] have been shown to be associated with the allocation of attentional resources and perceptual-cognitive resources, respectively (Hancock, 2007). Because it is often observed after an "oddball" sensory stimulus, the P3 (resulting from an auditory, tactile or visual stimulus and strongest when the stimulus occurs in an attended sensory modality – Driver and Spence, 1998) is thought to be related to unexpected occurrences and has been used successfully in Rapid Serial Visual Presentation (RSVP) (Gerson, Parra and Sajda, 2006) to triage large imagery mosaics. Further, because of the oddball stimulus correlation, the P3 may be applicable in aviation where the pilot observes something but because he is attending to other duties, may not notice or react to it in time. If the system recognizes the characteristic P3 signal without an accompanying pilot reaction, it may be possible to alert the pilot to the presence of an un-attended object or event that requires attention. Peterson, Allison, and Polich (2006) found that workload-related Alpha signals have an inverse correlation with P3 signal during computer games of various workload levels and they recommend monitoring these various spectral signatures simultaneously to improve accuracy. Trejo, et al. (2006) studied the impact of mental fatigue on EEG rhythms and found an increase in frontal Theta and parietal Alpha power, though their ERP (N1, P2 and P3) data were inconclusive. By monitoring various ERPs, it may be possible to use the information to monitor operator state – the intended goal of AugCog – to determine what cue or event was attended to, or whether it was missed, and when.

Using Real-Time Measures to Improve Training Performance

During a training session, an individual requires mental effort to acquire the skills necessary to complete the task. However, as they go through the three levels of skill development,[25] they require less and less effort to do so until they reach the point of automaticity.[26] Stevens, Galloway and Berka (2006) demonstrated that as trainees acquired expertise, their engagement and workload decreased as noted by their EEG patterns. Berka et al. (2006) noted differences in the Theta band EEG signals between individuals who made correct and incorrect decisions thus providing a potential metric to determine true skill level. Marshall, Pleydell-Pearce and Dickson (2002) found that as individuals gain proficiency in a task, they may change their strategy of where, when, and for how long they gaze at various instruments. By measuring the gaze point during the training sessions, it can be determined when the individual gains insight and understanding of the structure of the task and develops a new strategy which may

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[23] Brain wave rhythms are divided into: Delta (0.5 to 3 Hertz [Hz]), Theta (4 to 7 Hz), Alpha (8 to 12 Hz), Beta (13 to 30 Hz), and Gamma (greater than 30 Hz), (Scerbo, Freeman, Mikulka, Parasuraman, DiNocero, and Prinzel 2001).

[24] Event Related Potentials (ERP) are non-volitional EEG responses that generate a voltage – either negative (N) or positive (P) occurring within a specific timeframe – after an observed event. The P3 (also called the P300) is a positive voltage that occurs roughly 300 milliseconds after a sensory stimulus and the N1 is a negative voltage that occurs roughly 100 milliseconds after a stimulus.

[25] These are: the *initial learning or cognitive stage* where the trainee assembles new knowledge, the *associative stage* where the trainee begins to automate the learned steps and the *autonomous stage* where the trainee executes the steps with minimal conscious mental effort.

[26] See also "chunking," a mnemonic device sometimes used to enable the intermediate learning steps.

indicate a change in their level of expertise. For example, if the pilot changes from a general sweep of all cockpit instrumentation, and starts relying more on the *predictive* instruments (Wickens, 2007; Endsley, 2000), it may be a sign that they have reached a new level of expertise in the task. All aspects of training may be affected by the ability to acquire real-time assessments of vigilance, workload, fatigue, engagement, and the ability to assess task proficiency status by observing an increase in SA, a drop in workload or a change in strategy. Rather than relying on outcome-based performance measures, which may inaccurately reflect skill level, it allows the training curriculum to be assessed for statistical timelines and effectiveness. These could be applied during training scenarios to ensure that it is having maximum impact on the trainee without the adverse "cognitive states such as distraction, boredom, confusion and frustration" (Stevens, Galloway and Berka, 2006) by capturing real-time EEG indicators such as engagement (involving information-gathering, visual scanning, and sustained attention) and workload index (which increases with working memory load and with increasing difficulty level of mental arithmetic). It may also be possible to use psychophysiological monitoring on test subjects to evaluate display modalities, symbology, and procedures and be able to capture – in real time – the points during the presentation where workload is high and situation awareness is low.

Adaptive Automation

Automation in advanced technology is occurring, dictated by the continuous movement towards more complex systems. While this has worked well in areas such as the automotive industry with the automatic transmission and anti-lock braking, it has also had negative consequences in situations where the human is excluded from the loop and serves simply as a system monitor. Doing so can have negative consequences because it engenders a time penalty required for the human to notice, understand and react to an important event as well as: 1) loss of vigilance and increased complacency (by placing too much trust in the automation), 2) loss of SA by becoming a passive observer rather than an active participant, and 3) the changed nature of the information or feedback available to the operator (Endsley, 1996). A newer approach is *adaptive automation*, where the level of automation is dynamically initiated and adjusted either by the system or by the operator to optimize engagement or vigilance without producing cognitive overload. Here, the support is enabled when workload is high or when some impairment becomes evident (Hancock, 2007); similarly to the way a pilot would off-load tasks to another crewmember.[27] Traditional automation rigidly changes the role of the user from that of an active participant to that of a passive observer, potentially disengaging them and opening up the possibility that they might miss key events or signals or critical warning signs. Adaptive automation, however, changes the paradigm by enabling assistive automation only when necessary.

While the details of how to enable adaptive automation in the cockpit is beyond the scope of this chapter, it would appear that the HMD can play a key role as part of the system, perhaps acting as the portal through which automation-level-dependent information could *flow to* the pilot (in the form of cognitively pre-digested cues and symbology) and simultaneously, key psychophysiologically-measured operator status data (such as EEG, ERP or eye metrics) could *flow back to* the system (Schnell, 2008). Since the response time between the event and the psychophysiological marker can be on the order of seconds or less, having these real-time indicators could very rapidly invoke the required automation to either immediately reduce pilot workload or take over aspects of the aircraft as necessary. Future research could indicate not only *when* the pilot is overloaded, but *which* of the pilot's resources may be affected, what Scerbo et al. (2001) refer to as Operator Modeling, where an impaired status indicator (from eye metric, EEG or ERP signal) initiates the automated response.

In the studies at Boeing's Phantom Works, information displayed during the simulation would "grey-out" when the pilot subjected himself to a high-g loading in a manner similar to what they would actually experience (Proctor, 1999). In a system equipped with adaptive automation, the aircraft would determine or sense the pilot's

[27] With an accompanying "I've got it" from the automated system.

physiological state as a result of excessive g-loading and simplify or reduce the HMD symbology or, alternatively, take over aircraft control entirely to prevent a catastrophe.

Bonner, Taylor, Fletcher and Miller, (2000) have designed a system called the Cognitive Cockpit intended to adapt to the cognitive state of the pilot by off-loading the more routine flight activities at need. This allows the pilot to focus more energy on the tactical aspects of the situation. The Tasking Interface Monitor ensures that mission goals are maintained and allows the system to assume control of generic tasks that are more rule-based and skill-based.

Albery and colleagues at the Air Force Research Lab have created the Disorientation Analysis and Prediction System (DAPS) as part of the Spatial Orientation Retention Device (SORD) to calculate a “disorientation index” and provide multi-sensor cueing to the pilot that recovery from a non-normal flight attitude may be required should the pilot be disoriented or be unaware of the problem (Albery, 2006, 2007).

Summary

- The HMD provides a unique method of presenting information to the pilot that replicates natural human exploratory behavior, allowing movement of head and eyes outside the limited field-of-regard of typical cockpit displays as the pilot navigates through the environment.
- Situation awareness is the ultimate goal of the display designer. The problem for the pilot is that there is often too much unprocessed data and not enough distilled information to be able to arrive at situation awareness through the information gathering, model making/updating and predicting cycle. Information must be presented in such a way as that it will be easy to understand to make the SA cycle easier and more intuitive, requiring less of the pilot’s already-taxed cognitive resources
- HMD symbology should be used to present flight and aircraft status that is not just a re-mapping of the internal cockpit display information but which is cognitively processed so as to provide useful predictive information without cognitive overload and which will allow the pilot to spend more time looking outside the cockpit to reduce the workload associated with the three steps in the situation awareness loop.
- There has been considerable study in the areas of attention, multiple resources and cross-modal integration which can explain how we can sometimes multi-task efficiently, but at some point become cognitively overloaded due to executive control overload. These models can also help identify ways to improve pilot performance using cross-modal cues as notifiers of an event in a complementary sensory modality, such as a 3-D audio cue directing the pilot’s attention to a visual event.
- Psychophysiological monitoring (such as eye metrics, respiratory and skin response and EEG or ERP signals) has been shown to accurately measure SA status, fatigue, disorientation, cognitive overload and *underload*, task expertise and correct or incorrect responses in various situations, with the HMD serving as a convenient platform for the sensors. Using these measures as system inputs – the focus of the AugCog program – can provide a real-time understanding of operator status during flight and training.
- Using an operator performance model and real-time psychophysiological measures of the pilot’s physical or cognitive state, immediate steps can be taken to allocate or off-load less urgent tasks to the aircraft system or to control the aircraft when the pilot becomes physically or cognitively incapacitated.

From advances in neuroergonomics – the science of understanding the way in which humans perceive information with a look towards improving our interaction with technology in the real world – valuable insights into how the HMD can advance past its current state as an extension of the aircraft display suite can be gained. We can start to improve integration with the aircraft through new developments in symbology, addition of ancillary cueing from tactile or 3-D audio and real-time operator status monitoring where the HMD – now a cognitive prosthesis – provides real-time assistance by closing the loop between the pilot and the aircraft.

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